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Kinetic model for torrefaction of wood chips in a pilot-scale continuous reactor

Lei Shang[a], Jesper Ahrenfeldt[a,*], Jens Kai Holm[b], Lars Stougaard Bach[a], Wolfgang Stelte[c], Ulrik B. Henriksen[a]

[a] Department of Chemical and Biochemical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
[b] Technology Solutions, DONG Energy Thermal Power A/S, Nesa Alle 1, 2820 Gentofte, Denmark
[c] Centre for Biomass and Biorefinery, Division for Energy and Climate, Danish Technological Institute, Gregersensvej 1, 2630 Taastrup, Denmark

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ABSTRACT

Torrefaction is a mild thermal treatment (200–300 °C) in an inert atmosphere, known to increase the energy density of biomass by evaporation of water and a proportion of the volatiles. In this work a "two-step reaction in series" model was used to describe the thermal degradation kinetics of pine wood. The kinetic parameters were determined using a thermogravimetric analyzer (TGA) and the mass loss during the initial heating period was taken into account when deriving the kinetic parameters. It was shown that the experimental results at different heating rates (10–50 °C min^{-1}) are in good accordance with the model data. In an additional step a continuous, pilot scale reactor was built to produce torrefied wood chips in large quantities. The "two-step reaction in series" model was applied to predict the mass yield of the torrefaction reaction. Parameters used for the calculation were the temperature along the reactor and the biomass feeding rate in combination with the kinetic parameters obtained from the tests in the TGA. Together with results from a laboratory scale, batch torrefaction reactor that was used to determine the higher heating value (HHV) and mass loss (y) of the same material at different torrefaction temperatures, it was possible to predict the HHV of torrefied wood chips from the pilot reactor. The results from this study and the presented modeling approach can be used to predict the product quality from pilot scale torrefaction reactors based on small scale experiments and could be used to improve the homogeneity of torrefied products, which still is a problem for most operational torrefaction pilot plants today.

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1. Introduction

Torrefaction is a mild thermal (200–300 °C) pretreatment in an inert atmosphere used to upgrade the fuel properties of lignocellulosic biomass. During the process, water and a part of the volatiles are released, causing a decrease in mass and an increase in energy density at the same time [1–6]. The energy density of fuel pellets produced from torrefied biomass can reach up to 14 000 MJ m^{-3} which is similar to a low rank coal [7–10]. The energy required for grinding of torrefied biomass can be reduced by 70–90% compared to untreated biomass [2]. Torrefied biomass has been shown to have hydrophobic properties improving its moisture resistance and potential for outdoor storage [11,12]. These property changes favor the replacement of fossil fuels with torrefied biomass in connection with co-milling and co-firing with coal in large utility boilers.

Most existing torrefaction studies today focus on the property changes of biomass in batch-scale reactors, and the torrefaction degree is calculated based on the determined weight loss. [3,12]. However, in large-scale production facilities, torrefaction is carried out in a continuous way and with a closed collector to create an inert atmosphere, which makes process control more challenging. In order to improve the process control for continuous torrefaction reactors it is desirable to develop a mathematical model that can describe the torrefaction reaction accurately under different heating rates. In practice, thermogravimetric analysis (TGA) is the most common technique for solid-phase thermal degradation studies [14–16]. The aim of kinetic evaluation of TGA data is to obtain relatively simple models, describing the torrefaction of biomass [17]. There is plenty of research data [18] related to pyrolysis of biomass under both dynamic (non-isothermal) and steady-state (isothermal) conditions. The main advantage of determining kinetic

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* Corresponding author. Tel.: +45 2132 5344; fax: +45 4677 4109.
E-mail address: jeah@kt.dtu.dk (J. Ahrenfeldt).

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parameters using a non-isothermal method is that only a single sample is required to calculate the kinetics over an entire temperature range in a continuous manner. However, it is widely agreed that multiple heating rates should be adopted to enhance the accuracy of the non-isothermal method [18].

Existing torrefaction kinetic studies [19–21] were exclusively conducted under isothermal conditions. Prins et al. [21] used a two-step reaction in series model to describe the weight loss kinetics of willow torrefaction. This model was earlier introduced by Di Blasi and Lanzetta [22] for studying the intrinsic kinetics of isothermal xylan degradation under inert atmosphere in the temperature range of 200–340 °C. They found that a one-step global reaction did not fit the experimental results satisfactorily, because the time derivative of the solid mass fraction as a function of temperature exhibited multiple maxima. Two-step models, however, was taken into account a competitive formation of volatile and solid compounds during torrefaction. In a study by Branca and Di Blasi on beech wood torrefaction [23], it was suggested that the first step was due to the degradation of extractives and the most reactive fractions of hemicelluloses, and the second step was due to the degradation of cellulose and part of lignin and hemicelluloses. For temperatures above 327 °C a third step was identified and it was suggested that it could be attributed to the degradation of lignin and small fractions of the other two constituents. Both studies observed that the first step is faster than the second step. Di Blasi and Lanzetta [22] pointed out that using slow heating rate to attain the isothermal stage in order to avoid intra-particle temperature gradients usually result in a significant weight loss during the heating stage. As a consequence from these results high heating rates (40–70 °C s^{-1}) were adopted. The char yield was determined as a function of the sample size prior to the tests to ensure no influence from the temperature spatial gradients. Constant char yields were attained for a sample thickness below 100 μm, and a particle size of 50 μm was chosen for the test. The results showed that the fraction of mass loss for the beginning of the isothermal stage was in the range of 0–0.16. It was therefore decided that these data can be analyzed by applying an isothermal model.

The intrinsic kinetics of torrefaction has been studied for wheat straw in one of our previous studies [13] using a two-step first order reaction in series model. Our study differs from the previous ones by taking into account the mass loss during the heating period when deriving the kinetic parameters which is not the case when the kinetic parameters are derived from the isothermal phase of a torrefaction reaction. Modeling results based on parameters taking into account, the heating phase of the reactor was in better accordance with experimental results. For the present study it was therefore decided to use the same methodology for deriving the kinetic parameters of wood chips during torrefaction. Torrefaction was also carried out in a continuous pilot-scale reactor. Sample temperatures recorded during the reaction were used to estimate the residual mass of torrefied wood chips by neglecting the heat transfer within wood chips. Repellin et al. [20] have shown in an earlier study that the time for the internal heat transfer within a wood chip that has a similar size is significantly short compared to the heating rate and residence time of the torrefaction (e.g. at 200 °C this characteristic time was 8 s for beech and 11 s for spruce). It was also concluded that for a residence time of more than 20 min, the weight loss depends almost entirely on the torrefaction temperature.

In the present study torrefaction was carried out using a lab scale batch reactor operated from 200 to 300 °C in 20 °C to determine the correlation between mass and energy loss, resulting in a curve that allows the prediction of the HHV based on the mass and energy balance. This correlation becomes very useful for continuous torrefaction processes where it is not possible to determine the weight and energy loss while it is operating. The only measurable parameters are temperature and retention time. The model developed during this study links these two properties together and allows a better process control according to a desired heating value of the product. It may therefore be a useful tool to improve the product homogeneity of continuous large-scale torrefaction units.

2. Experimental

2.1. Materials

The raw material used for this study was pine wood chips (*Pinus sylvestris* L.) from Zealand, Denmark (55°30′ N 11° 45′ E). The size of the chips varied from 30 mm × 30 mm × 20 mm to 100 mm × 100 mm × 30 mm. The chips were stored for several months in a shielded container with air circulation and had a moisture content of about 16% on wet mass basis. Prior to the TGA experiment, wood chips were milled and particles smaller than 90 μm were collected. The cell wall composition and proximate analysis of the wood chips raw material are listed in Table 1. The amount of extractives in the sample was not determined, and hemicelluloses were analyzed as the sum up of xylose, galactose, and mannose. Detailed descriptions of the analysis methods can be found in our previous works [3].

2.2. Thermogravimetric analysis

Torrefaction of wood chips was carried out using a TGA (TG 209 F3, NETZSCH, Germany) with a nitrogen flow rate of 40 cm^3 min^{-1}. Tests were made between 250 and 300 °C at heating rates of 10 and 50 °C. The sample weight varied from 3 to 5 mg, and ceramic crucibles were used for the test. For complete drying before running the test the samples were heated up to 105 °C at a rate of 20 °C min^{-1} and held for 3 min to remove all remaining moisture. Subsequently the samples were heated to the desired torrefaction temperature and held for 90 min. Afterwards, purge gas was switched from nitrogen to air and the sample was heated to 850 °C for 50 °C min^{-1} and kept at this temperature for 5 min for complete combustion. The residual mass was defined as the ash content to be used in the model calculations in Eq. (11). Two tests were conducted for each condition, and good reproducibility was achieved.

2.3. Torrefaction in a batch reactor

For determining the relationship between sample mass loss during torrefaction and HHV of the torrefied product, a batch scale torrefaction reactor was used as described in [16]. For each test, wood chips were pre-dried in an oven at 104 °C for 24 h and subsequently placed in an air tight metal reactor (15 cm × 31 cm × 10 cm) with gas in and outlet, and a thermocouple centered in the reactor. The reactor was placed in an oven (type S 90, Lyngbyovnen,

Table 1
Chemical and proximate analysis (d.b.) of oven dried wood chips.

	Cell wall composition			Proximate analysis			
	Lignin	Cellulose	Hemicellulose	Moisture	Volatiles	Fixed carbon	Ash
Wood chips	27.5	42.8	15.9	1.06	82.43	15.26	1.3

Denmark) with heating rate of 6 °C min^{-1}. Nitrogen was flushed through the reactor at a flow rate of 500 $\text{cm}^3\,\text{min}^{-1}$, and the gas outlet was heated to avoid condensation. Torrefaction was carried out at temperatures ranging from 200 to 300 °C for about 2 h (from the thermocouple inside the reactor reached the torrefaction temperature until the start of cooling). Temperatures at different places in the reactor were also measured without sample during torrefaction, and the difference was within 5 °C.

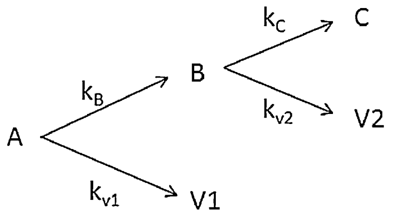
The anhydrous weight loss (AWL) was defined as the mass fraction lost during torrefaction. The ash content was determined in a muffle furnace heated to 550 °C for 3 h, two repeated measurements carried out for each torrefaction condition. The HHV was determined using a bomb calorimeter (6300, Parr Instrument Company, USA). Prior to testing, the samples were passed through a cutting mill (SM2000, Retsch, Germany) and only particles smaller than 0.6 mm were chosen for the test. At least two measurements were taken for each condition. The energy yield was defined as the fraction of heating value retained in the wood chips after the torrefaction. $HHV_{104^\circ\text{C}}$ defines the HHV of oven dried wood chips (Eq. (1)):

$$\text{Energy yield}_{(\text{daf})} = \frac{\text{HHV}_{(\text{daf})}}{\text{HHV}_{104^\circ\text{C}(\text{daf})}} \times (100 - \text{AWL}_{(\text{daf})}) \tag{1}$$

2.4. Torrefaction in pilot scale

An screw conveyor reactor (Fig. 1) with feeding capacity of 6 kg h^{-1} was used to produce torrefied wood chips in pilot scale. The reactor was indirectly heated by burning liquefied petroleum gas. A nitrogen flow of 2.5 L min^{-1} was used as a carrier gas in the torrefaction reactor and the collector unit throughout the whole test run to avoid ignition. The temperature of the flue gas was controlled by adjusting the gas and air volume, and the temperature of reaction was monitored by totally 11 thermocouples located in different places through the reactor. The residence time was controlled by adjusting the rotation speed of the screw conveyor. Torrefaction was carried out at 250 and 280 °C with residence time of 1 h.

2.5. Kinetic modeling



(2)

$$\frac{d[A]}{dt} = -(k_B + k_{V1})[A] \tag{3}$$

$$\frac{d[B]}{dt} = k_B[A] - (k_C + k_{V2})[B] \tag{4}$$

$$\frac{d[C]}{dt} = k_C[B] \tag{5}$$

A two-step reaction in series model, as shown in scheme (2), is used to study the kinetics of torrefaction. The xylan is denoted '*A*', and '*B*' is the intermediate compound, which is a solid with a reduced degree of polymerization. '*V*1' and '*V*2' are volatiles; '*C*' is the solid residue. By applying the proposed model, rate equations can be obtained, as shown in Eqs. (3)–(5), for solids by assuming first order reactions [22], where *k* is the rate constant for each step, expressed in s^{-1}. Integration of differential equations, with the initial condition that only A is present at the beginning of the reactions, the mass of the solid residues (*M*) can be expressed as shown in Eqs. (6)–(10).

$$\frac{M - M_\infty}{M_0} = \lambda_1 \cdot e^{-K_1 \cdot t} + \lambda_2 \cdot e^{-K_2 \cdot t} \tag{6}$$

where

$$\frac{M}{M_0} = [A] + [B] + [C] \tag{7}$$

$$\lambda_1 = 1 + \left[\frac{k_B \cdot K_1 - k_B \cdot k_C}{K_1 \cdot (K_2 - K_1)}\right], \quad \lambda_2 = \frac{-k_B \cdot K_2 + k_B \cdot k_C}{K_2 \cdot (K_2 - K_1)} \tag{8}$$

$$\frac{M_\infty}{M_0} = \frac{k_B \cdot k_C}{K_1 \cdot K_2} \tag{9}$$

$$K_1 = k_B + k_{V1}, \quad K_2 = k_C + k_{V2} \tag{10}$$

M_0 is the initial sample mass on ash free basis; M_∞ is the final char yield [*C*] when time is sufficiently long. M/M_0 can be determined experimentally by

$$\left(\frac{M}{M_0}\right)_{\text{exp}} = \frac{m_{TGA} - m_{ash}}{m_0 - m_{ash}} \tag{11}$$

where m_0 is the initial sample mass, m_{ash} is the mass of ash in the sample and m_{TGA} is the mass measured by TGA as a function of time.

Di Blasi and Lanzetta [22] used a graphical method to determine the kinetic parameters by taking the logarithm of Eq. (6):

$$\ln\left(1 - \frac{M_0 - M}{M_0 - M_{B^*}}\right) = -K_1 \cdot t \tag{12}$$

$$\ln\left(1 - \frac{M_{B^*} - M}{M_{B^*} - M_\infty}\right) = -K_2 \cdot (t - t^*) \tag{13}$$

where t^* is the demarcation time, which separates the first and the second step. Consequently, M_{B^*} is the maximum value of the reaction intermediate mass, which occurs at time t^*. If the left side of Eqs. (12) and (13) is plotted against time for different temperatures, K_1 and K_2 can then be obtained from the slope of these sets of straight lines. Arrhenius plots are then used to get activation energies, *Ea*, and pre-exponential factors, *A*:

$$\ln k = \ln(A) - \frac{Ea}{R \cdot T} \tag{14}$$

Prins et al. [21] mentioned that an exact demarcation time is difficult to establish for their results due to overlapping of the reaction steps. They used a numerical approach (MATLAB) shown in Eq. (15) to fit all kinetic parameters by minimizing the sum of squares function:

$$F = \sum_i \left[\left(\frac{M}{M_0}\right)_{\text{exp},i} - \left(\frac{M}{M_0}\right)_{theor,i}\right]^2 \tag{15}$$

For the present study the demarcation time was determined based on a numerical approach that has been reported in one of our earlier studies about the torrefaction of wheat straw [13]. Slow heating rates (10 and 50 °C min^{-1}) were used to avoid intra-particle temperature gradients, and weight loss during heating stage was taken into account when deriving the kinetic parameters from the isothermal stage as shown in Eqs. (16)–(19):

$$At \quad t = 0 \quad [A] = [A]_0, \quad [B] = [B]_0, \quad [C] = [C]_0$$

Integration of Eqs. (3)–(5) with the above-mentioned initial conditions gives

$$[A] = [A]_0 \exp(-K_1 t) \tag{16}$$

$$[B] = \frac{k_B[A]_0}{K_1 - K_2}[\exp(-K_2 t) - \exp(-K_1 t)] + [B]_0 \exp(-K_2 t) \tag{17}$$

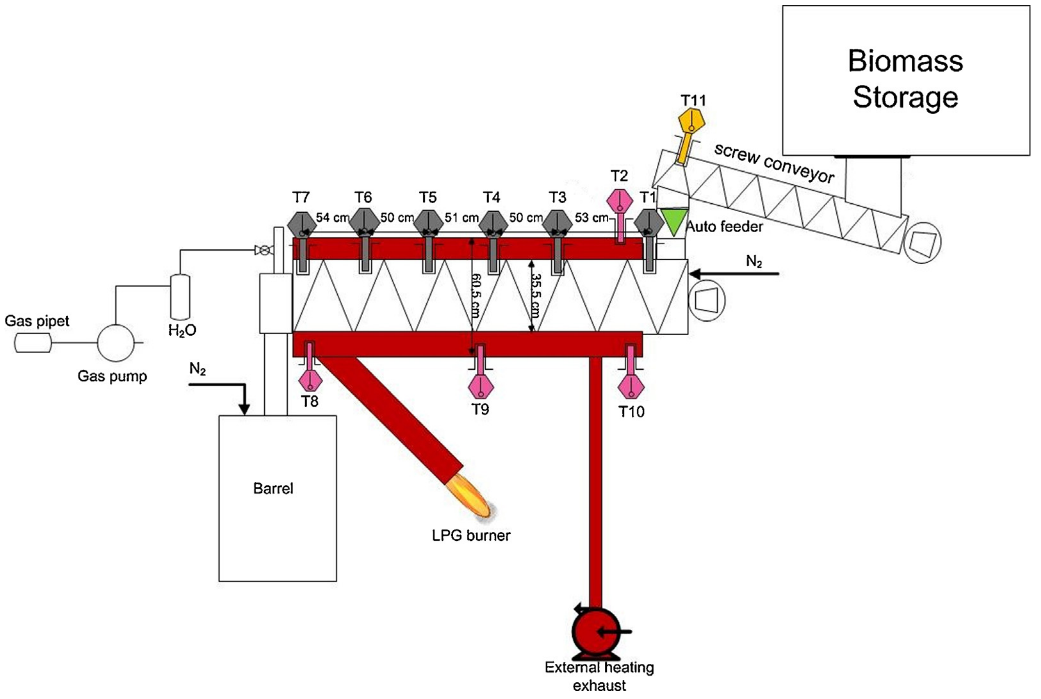


Fig. 1. Illustration of the screw conveyor torrefaction reactor and feeding system built in DTU Risø campus, Denmark. T1–T11 are 11 thermocouples measuring the temperatures in the feeder (yellow), in the reactor (gray), and in the heating gas (pink). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

$$[C] = [C]_0 + \frac{k_C(k_B[A]_0 + K_1[B]_0)}{K_1K_2} + \frac{k_Bk_C[A]_0\ \exp(-K_1t)}{K_1(K_1-K_2)} - \frac{k_Bk_C[A]_0\ \exp(-K_2t)}{K_2(K_1-K_2)} - \frac{k_C[B]_0\ \exp(-K_2t)}{K_2} \tag{18}$$

$$\left(\frac{M}{M_0}\right)_{theor} = [A]+[B]+[C] \tag{19}$$

A schematic drawing of the algorithm taking into account the chemical composition change at the onset of the isothermal period is shown in Fig. 2. In the first iteration it was assumed that the entire solid is A, with no B and C. With this initial assumption and a starting guess of k_B, k_{V1}, k_C, k_{V2}, which were based on values found in Prins et al. [21], nonlinear optimization using the MATLAB (version R2008b) routine ‘lsqcurvefit’ was made with the default tolerance settings. The ‘lsqcurvefit’ is based on the Niedler–Mead optimization algorithm and used to minimize the root mean square of the difference between the calculated and experimental data. Following this, at each temperature the four pre-exponential factors (A) and activation energies (Ea) were calculated by means of Arrhenius plot. With these calculated values the initial concentration of the isothermal period for A, B, and C can be obtained by Eqs. (20)–(22), and then used as input for the optimization. The calculations were done by numerical solution of the three coupled first order differential equations, as shown in Eqs. (3)–(5). To account for the heating rate, the chain rule was used to transform the equations into the temperature dependent form shown in Eqs. (20)–(22). From the second iteration onwards the calculated A and Ea were used to provide the starting guess for the Niedler–Mead optimization. The procedure was repeated until stable values for the A and Ea were reached.

$$\frac{d[A]}{dT} = \left(\frac{dt}{dT}\right)\cdot\{-(k_B+k_{V1})[A]\} = \frac{1}{\beta}\cdot\{-(k_B+k_{V1})[A]\} \tag{20}$$

Table 2
Kinetic parameters in the reaction rate constants obtained from TGA tests.

	A (s^{-1})	Ea ($J\,mol^{-1}$)
k_B	77.14	46 854
k_{V1}	2.68×10^8	122 110
k_C	1×10^{-5}	0.0061
k_{V2}	5.75×10^4	94 396

$$\frac{d[B]}{dT} = \frac{1}{\beta}\cdot\{k_B[A]-(k_C+k_{V2})[B]\} \tag{21}$$

$$\frac{d[C]}{dT} = \frac{1}{\beta}\cdot\{k_C[B]\} \tag{22}$$

where β is the heating rate in $°C\,s^{-1}$.

3. Results and discussion

3.1. Kinetic parameters and model verification

The kinetic parameters obtained by fitting the experimental data at 250, 260 °C from TGA (at a heating rate of $10\,°C\,min^{-1}$) and at 250, 260, 270, 280, 290 °C (at a heating rate of $50\,°C\,min^{-1}$) are shown in Table 2. 180–190 pairs of time–mass yield data points have been used for each temperature. Fig. 3 shows the Arrhenius plots used for determining the activation energy and pre-exponential factors.

In agreement with literature, the first step is much faster than the second step. Solid yields for the two reaction steps decreased from 90% and 32% at 250 °C to 68% and 7% at 300 °C, respectively. Compared to the results from wheat straw in our earlier work [13], wood chips had a little higher solid yield at the first step but a much lower solid yield at the second step. It can also be seen from Table 2 that the rate constant k_C is close to zero. By looking at the mass curves of these two samples obtained from TGA, wheat straw

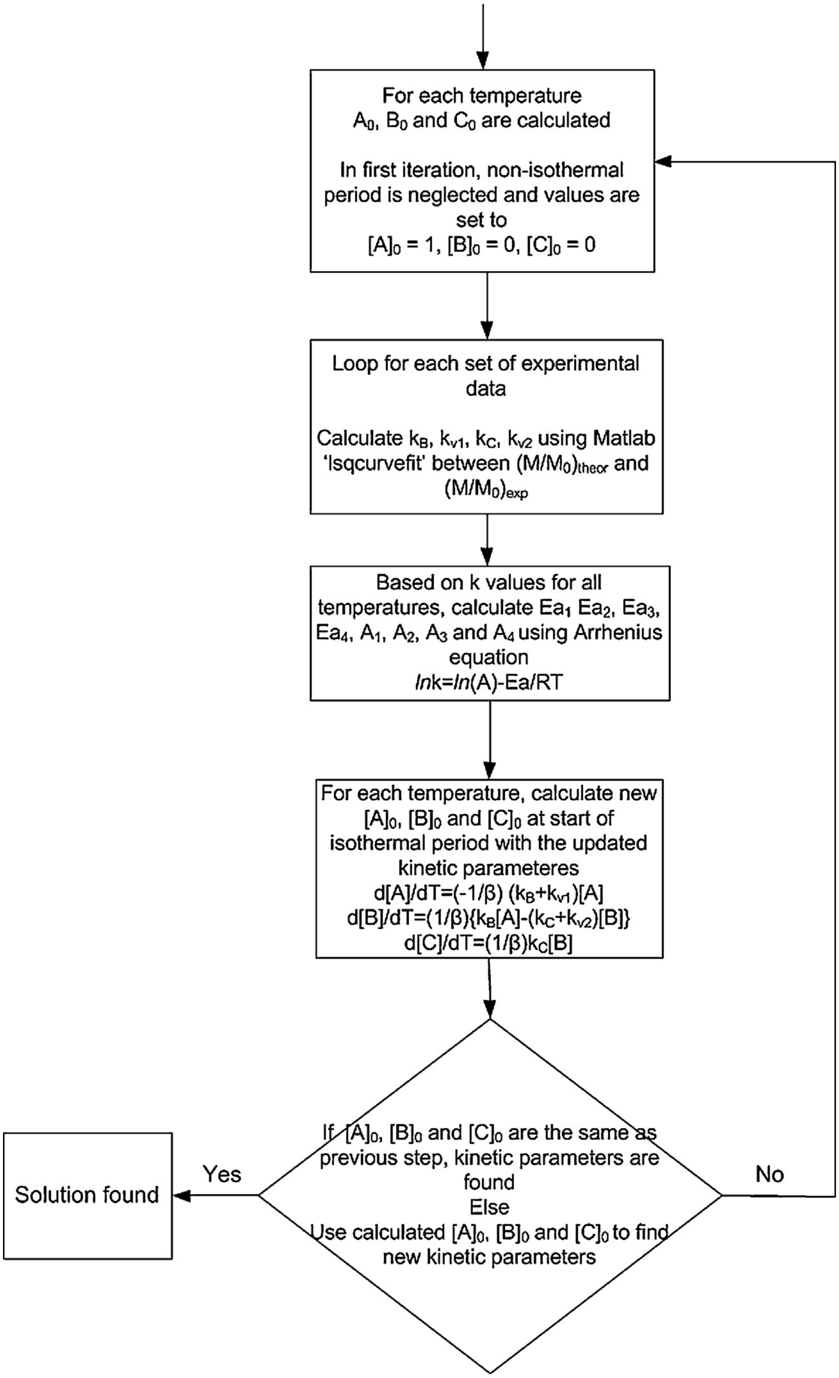

For each temperature
A0, B0 and C0 are calculated
In first iteration, non-isothermal period is neglected and values are set to
[A]0 = 1, [B]0 = 0, [C]0 = 0
Loop for each set of experimental data
Calculate kB, kv1, kC, kv2 using Matlab 'lsqcurvefit' between (M/M0)theor and (M/M0)exp
Based on k values for all temperatures, calculate Ea1 Ea2, Ea3, Ea4, A1, A2, A3 and A4 using Arrhenius equation
lnk=ln(A)-Ea/RT
For each temperature, calculate new [A]0, [B]0 and [C]0 at start of isothermal period with the updated kinetic parameteres
d[A]/dT=(-1/β) (kB+kv1)[A]
d[B]/dT=(1/β){kB[A]-(kC+kv2)[B]}
d[C]/dT=(1/β)kC[B]
If [A]0, [B]0 and [C]0 are the same as previous step, kinetic parameters are found
Else
Use calculated [A]0, [B]0 and [C]0 to find new kinetic parameters
Yes
No
Solution found

Fig. 2. Diagram of algorithm used in MATLAB for calculating kinetic parameters of wood chips torrefaction.

experienced a sharper weight loss in the beginning and reached a flat level quite early, while wood chips had a slight weight loss in the early stage but the weight loss continued until the end of the reaction.

In order to verify the model, experimental data were compared with the model results for both the non-isothermal part (heating period from 200 °C to final torrefaction at both heating rates) and the isothermal part. Results from both heating rates of 10 and 50 °C min^{-1} are shown in Fig. 4, and Fig. 5 shows the simulation results of *A*, *B*, and *C* at both heating rates. It can be seen that at higher temperature, the agreement between model and experimental data is not as good as at lower temperature. This is because the experimental data used to derive the kinetic parameters is only up to 260 °C for 10 °C min^{-1}, and 290 °C for 50 °C min^{-1}. The reason of not including all experimental data is due to that the heating rate of the TGA is limited to 80 °C min^{-1}, and thus while being heated to high temperature (e.g. 300 °C) major fraction of *A* will already be transformed to *B* during the initial non-isothermal phase of experiments. The kinetic parameters obtained in this way would not be able to describe the reaction for the whole range. At the same temperature, the residual mass in Fig. 4(b) was a bit lower than those in Fig. 4(a). This is due to the temperature

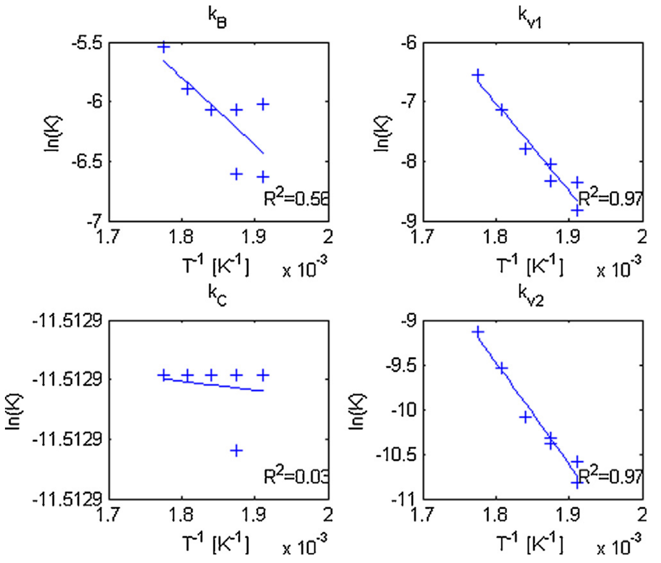


Fig. 3. Arrhenius plots for the computation of *A* and *Ea*.

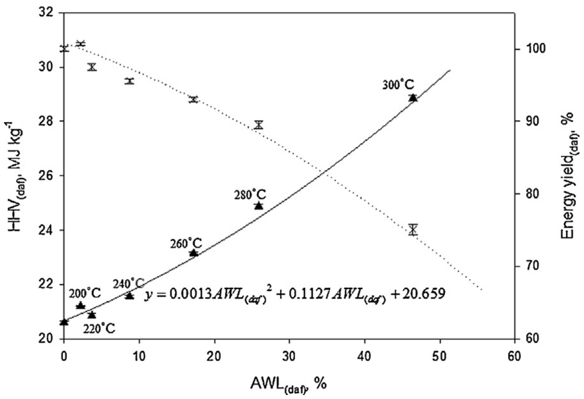


Fig. 6. Higher heating value (HHV) (▲) and energy yield (×) of torrefied wood chips vs. anhydrous weight loss (AWL, 0% AWL represents oven dried samples) on dry and ash free basis (daf).

overshooting problem in the TGA, the higher the set temperature (and/or the higher the heating rate) the larger the overshoot. The model has also been tested on torrefaction for 2 h (results not shown in this paper), and it was found that the model overestimated the mass loss, this trend may also be observed from Fig. 4 when the residence time exceeds 90 min. This means that the present model should be used with caution for torrefaction with long residence time.

3.2. Torrefaction in lab and pilot scales

In a lab-scale batch reactor, higher heating value (HHV) and mass yield were determined for wood chips torrefied at different temperatures, as shown in Fig. 6. Eq. (23) was established:

$$HHV_{(daf)} = 0.0013 \cdot y^2 + 0.1127 \cdot y + 20.659 \qquad (23)$$

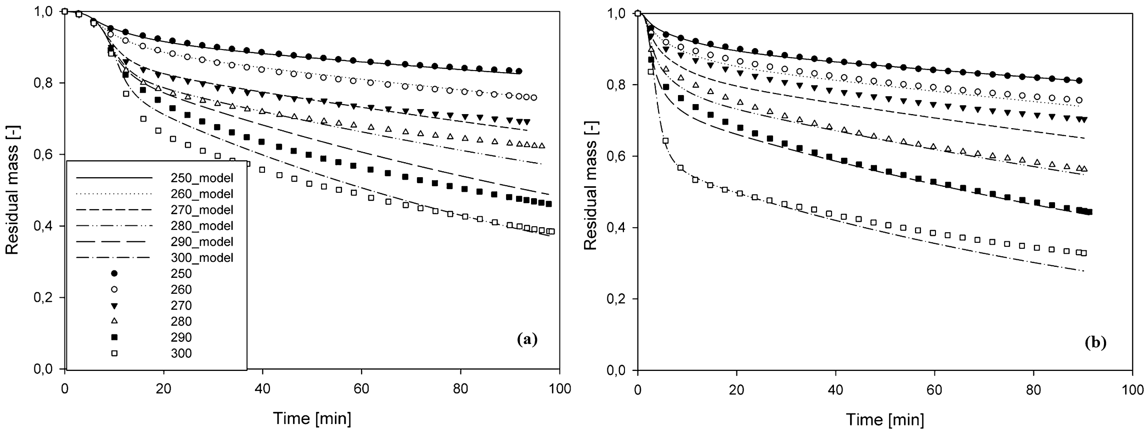


Fig. 4. Experimental and modeled relative weight (on ash free basis) of wood chips vs. time for (a) at heating rate of 10 °C min^{-1} and (b) at heating rate of 50 °C min^{-1}. Starting weight is defined at 200 °C; heating period from 200 °C to desired torrefaction temperature is included in the plot.

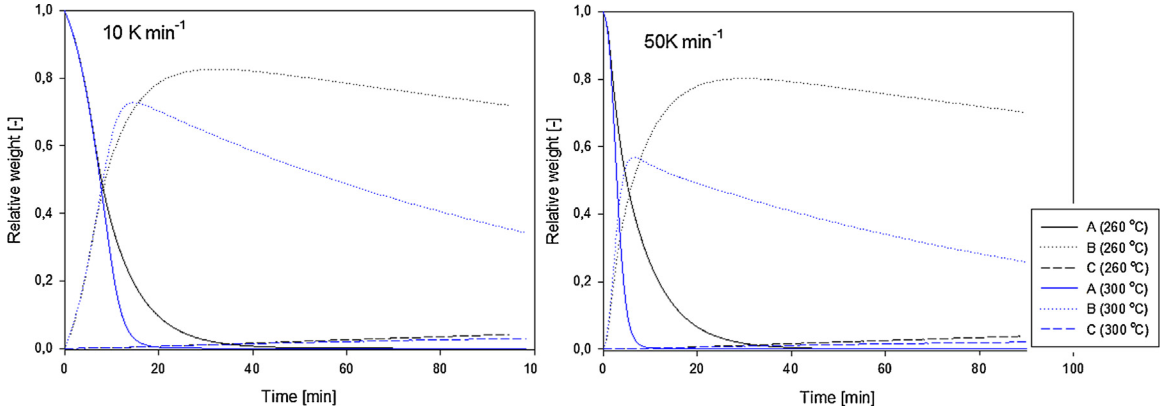


Fig. 5. Yields of *A*, *B*, and *C* at torrefaction temperature of 250 and 300 °C with heating rates of 10 and 50 °C min^{-1}. Starting weight defined at 200 °C, heating period from 200 °C is included in the plot.

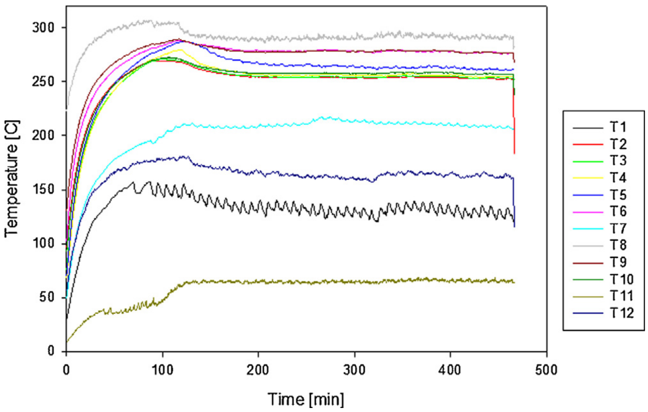


Fig. 7. Temperature diagram of a test at 280 °C in the pilot scale torrefaction unit. The legend notes correspond to the thermocouples in Fig. 1.

where y is the ratio of solid mass loss during torrefaction on dry and ash free basis (daf). The *energy yield* was defined as the ratio between total energy retained in the torrefied samples and in the oven dried samples. It can be observed that there is not a linear relationship between AWL and HHV/energy yield. There is a higher energy and mass loss at torrefaction temperatures ranging from 250 to 300 °C compared to the temperature range from 200 to 250 °C. This is because hemicelluloses start to decompose at 200–250 °C and the decomposition last until 300 °C, while cellulose and lignin start the degradation at 270–300 °C. In order to preserve energy in the torrefied material, lower torrefaction temperature and shorter residence time should be preferred. If a high energy density is desired, it is better to have more severe torrefaction conditions.

The model described by Eqs. (16)–(22), was also applied for the torrefaction of wood chips in a continuous pilot scale reactor, as shown in Fig. 1. An example of all the temperatures recorded by 11 thermocouples during torrefaction of 280 °C is shown in Fig. 7. For the test runs, the reactor was pre-heated for 1 h before wood chips were fed into the reactor. Thermocouple T6 was used to determine the torrefaction temperature. The temperatures recorded in the reactor (T1, T3, T4, T5, T6, T7) together with the speed of the screw conveyor and the distance between each thermocouple was used to obtain the temperature profile of the samples. The obtained profile was then used as input for the model to calculate the residual mass. The final mass yields of the torrefied wood chips were 83.42% at 280 °C and 92.45% at 250 °C, as shown in Fig. 8. Based on Eq. (23), the HHV can be calculated by inserting the final mass loss of torrefied wood chips predicted by the model. Calculated results and HHV determined experimentally using a bomb calorimeter from two torrefaction temperatures are plotted in Fig. 9. There is a good correlation between model results and experimental results.

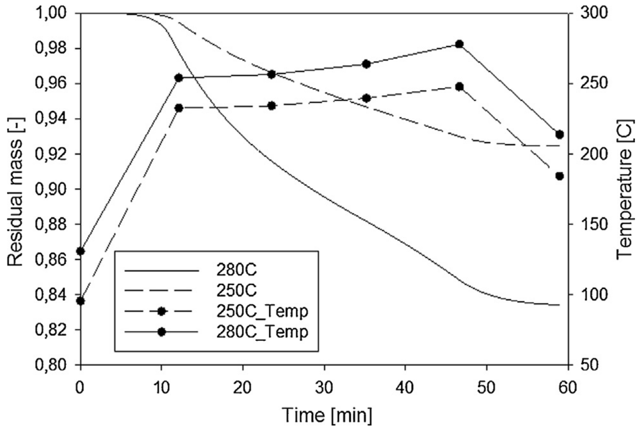


Fig. 8. The temperature profiles of wood chips in the pilot scale reactor during torrefaction at 250 and 280 °C, and the mass yield of torrefied wood chips calculated from the model on a dry and ash free basis.

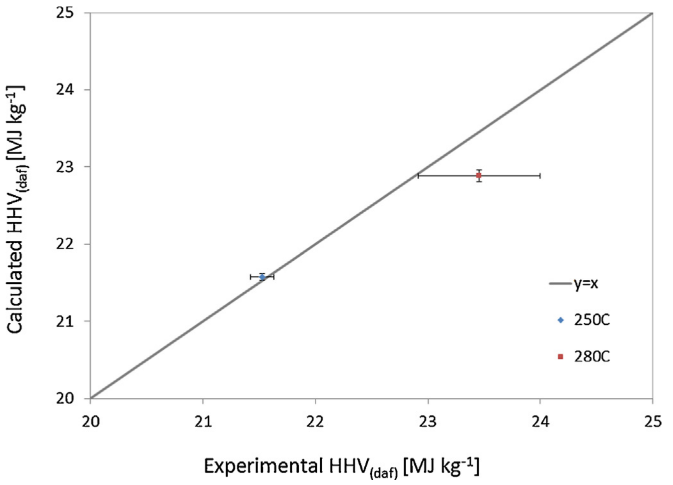


Fig. 9. Correlation between higher heating values (HHV) measured on the torrefied wood chips (at 250 and 280 °C) in a pilot scale reactor and calculated results from Eq. (23) by using the residual mass predicted from the model (as shown in Fig. 8). Both results are on dry and ash free basis. Error bars show the 95% confidence intervals.

4. Conclusion

A two-step first-order reaction in series model was used to study the kinetics of wood chips torrefaction in a TGA setup. In contrast to other studies, that are based on kinetic parameters obtained from the isothermal part of torrefaction and thereby neglecting the degradation of sample during the heating period, the present study took into account the mass loss during the heating period for calculating the kinetic parameters. The results show that parameters obtained in this way are in good accordance with the experimental results at different heating rates during the entire reaction. The model was also useful to predict the higher heating value of wood chips torrefied in a continuous pilot scale reactor. The kinetic parameters for modeling the continuous process were based on TGA experiments and data from a laboratory scale batch reactor that allowed correlating the HHV with the mass yield of a torrefaction reaction. It can be concluded from the study that the mass yield and HHV of torrefied products from a continuous torrefaction reactor can be predicted based on the temperature history of the sample. However, it needs to be noticed that the heat transfer was neglected in this study due to the slow heating rate used for torrefaction. For set-up with different heating rates or raw materials, the model should be used with caution.

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